HOW DOES LOWER EXTREMITY COORDINATION CHANGE BASED ON HEIGHT AND PHASE OF THE COUNTERMOVEMENT JUMP?

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While jumping is a fundamental movement skill, its coordination, especially at submaximal heights, is understudied. The purpose of this study was to use ground reaction force and 3D motion capture to understand how participants' (n = 16, age = 23.0 ± 3.60 years) coordination patterns change when performing countermovement jumps to multiple heights (25%, 50%, 75%, 100%) across three phases of the jump (unweighting, eccentric, concentric) using modified vector coding. With increasing jump heights, anti-phase coordination of the thigh-pelvis segment couple in the unweighting phase increased (F = 17.05, $p < 0.001$), while thigh-leading coordination decreased (F = 17.06, $p < 0.001$). This finding, along with multiple significant coordination pattern changes in the eccentric phase of the jump, creates a framework for improved performance cueing and rehabilitation.

KEYWORDS: intersegmental coordination, sport performance, kinetics, athletes.

INTRODUCTION: The vertical jump is a fundamental movement skill used to develop physical literacy in children, train high performance sport athletes, and test rehabilitation progress post-injury. The countermovement jump, a vertical jump with no pause at the bottom of the descent (Bobbert et al., 1996), is especially common in sports like basketball and volleyball. However, the countermovement jump is a complex movement to perform successfully and requires a high degree of upper and lower body coordination (Markovic, 2004). Coordination, defined as the "patterning of body and limb motions relative to the patterning of environmental objects and events" (Turvey, 1990, p.938), has been used to characterize the intersegmental movements that occur during the production of complex movement tasks. Based on kinematic output, intersegmental coordination values can provide information on observable differences in movement patterns during the execution of a countermovement jump more accesible to coaches and practitioners than underlying kinetic data. Additionally, coordination analyses have been found to be more sensitive to changes in movement patterns than conventional kinematic analyses (Smith et al., 2015), positioning intersegmental coordination as a key tool for coaches and practitioners.

Modified vector coding, a method to characterize intersegmental coordination (Chang et al., 2008) has only been used in one countermovement jump study to date (Raffalt et al., 2016), and none when considering the countermovement jump takeoff as three phases: unweighting, eccentric, and concentric (McMahon et al., 2018). Modified vector coding allows all movements to be categorized as one of four easily understandable intersegmental coordination patterns: in-phase (segments are rotating towards each other), anti-phase (segments are rotating away from each other), proximal-leading (only the proximal segment is rotating), or distal-leading (only the distal segment is rotating). By assessing the intersegmental coordination patterns in the countermovement jump across different heights and phases (unweighting, eccentric, concentric) of the jump, this research study aims to identify which intersegmental coordination patterns are most common and how they change across jump height conditions. In doing so, observable movement pattern changes across jump heights can hopefully be used in the field to improve performance training.

METHODS: Vertical ground reaction forces (Bertec Inc., Columbus, OH, USA) and 3D marker positions (Qualisys Track Manager, version 2020.3, Gothenburg, Sweden) were measured from participants performing countermovement jumps in four conditions: 25%, 50%, 75%, and

100% of their maximum jump height. To ensure each participant was jumping to the appropriate height, a rope was suspended from the ceiling and lowered such that the bottom of the rope was at the tip of the participant's fingers when reaching with one arm as high as they could. On the rope there were four tape markers indicating the participant's 25%, 50%, 75%, and 100% maximum jump height. The participants were asked to complete a countermovement jump and reach task and touch the tape marker specified for each jump height trial. Participants (n = 16, age = 23.0 ± 3.60 years, height = 1.73 ± 0.079 metres, weight = 67.11 ± 7.26 kilograms, jumping sport experience = 5.81 ± 5.48 years) completed eight jumps for each condition and each trial was separated from the next by 30 seconds of rest to mitigate the effects of fatigue. All 32 trials were performed in a random order.

Kinetic and kinematic data were sampled at 100Hz and filtered using a fourth-order Butterworth filter with a 10Hz cutoff. Jump height values were calculated using the flight-time method (Linthorne, 2001). For each participant, foot, shank, thigh, and pelvis segments were defined based on Winter's (2009) anthropometric table. For all trials, segment angles were quantified relative to the horizontal and calculated for the foot, shank, thigh, and pelvis segments. The jump trials were separated into unweighting, eccentric, and concentric phases based on the method of McMahon et al. (2018). Angle-angle plots were created for three segment couples: (1) thigh-pelvis, (2) shank-thigh, and (3) foot-shank. The proximal segment angle was plotted on the x-axis and the distal segment angle was plotted on the y-axis, for a total of 9 plots per trial (3 segment couples x 3 jump phases). Coupling angles were calculated as the angle between two adjacent points on the angle-angle plot. Once all coupling angles at all time points on the angle-angle plots were calculated, the coupling angles were identified as belonging to one of four coordination patterns that define the intersegmental relationship: (1) in-phase ($22.5° < \theta < 67.5°$, $202.5° < \theta < 247.5°$), (2) anti-phase ($112.5° < \theta < 157.5°$, $292.5° < \theta < 337.5°$), (3) proximal leading ($337.5° < \theta < 22.5°$, $157.5° < \theta < 202.5°$), (4) distal leading ($67.5° < \theta < 112.5°$, $247.5° < \theta < 292.5°$; Chang et al., 2008). For each participant, as all possible movements existed within one of four coordination patterns, we performed a frequency analysis to describe how often each coordination pattern occurred within a specific phase of the countermovement jump, for each segment couple — with the frequency of all four coordination patterns summing to 100% of the movement. The coordination pattern frequency proportion for each phase was calculated using the following equation:

$$\%_x = \frac{\Sigma x}{\Sigma n}$$

Where, Σx is the total number of samples of a specific coordination pattern x, and Σn is the total number of samples in the phase.

To test if coordination pattern frequency proportions were significantly different within-participants across normalized jumps heights, 36 one-way repeated-measures ANOVAs were performed separated by the phase of the jump and segment couple. The alpha value indicating a significant main effect of the ANOVAs was corrected using the Bonferroni method for multiple comparisons ($\alpha = 0.0014$).

RESULTS: Figure 1A –1I show the frequency distribution of the coordination patterns in the three phases of the countermovement jump and their significance across the jump height conditions. With increasing jump heights, the thigh-pelvis segment couple exhibited increasing anti-phase coordination ($F(1.56,23.44) = 17.05$, $p < 0.001$, $\eta_p^2 = 0.53$) and decreasing thigh-leading coordination ($F(1.89,28.28) = 17.06$, $p < 0.001$, $\eta_p^2 = 0.53$) in the unweighting phase, and decreasing in-phase coordination ($F(2.07,31.09) = 9.65$, $p < 0.001$, $\eta_p^2 = 0.39$), increasing anti-phase coordination ($F(2.03,30.46) = 11.77$, $p < 0.001$, $\eta_p^2 = 0.44$), and decreasing thigh-leading coordination ($F(3,45) = 8.45$, $p < 0.001$, $\eta_p^2 = 0.36$) in the eccentric phase. Additionally, the shank-thigh segment couple exhibited increasing thigh-leading coordination ($F(1.53,23.00)$

= 11.35, $p < 0.01$, $\eta_p^2 = 0.43$) in the unweighting phase, and decreasing anti-phase coordination ($F(2.26,33.94) = 7.92$, $p < 0.01$, $\eta_p^2 = 0.35$) and increasing thigh-leading coordination ($F(1.93,28.92) = 16.74$, $p < 0.001$, $\eta_p^2 = 0.53$) in the eccentric phase, with increasing jump heights. Finally, the foot-shank segment couple only exhibited increasing anti-phase coordination ($F(3,45) = 15.14$, $p < 0.001$, $\eta_p^2 = 0.50$) in the eccentric phase with increasing jump heights. Coordination pattern frequency in the thigh-pelvis segment couple had the greatest number of significant main effect differences with increasing jump heights, while the foot-shank couple had the fewest. Additionally, the eccentric phase had the greatest number of coordination pattern frequency differences, while the concentric phase had none.

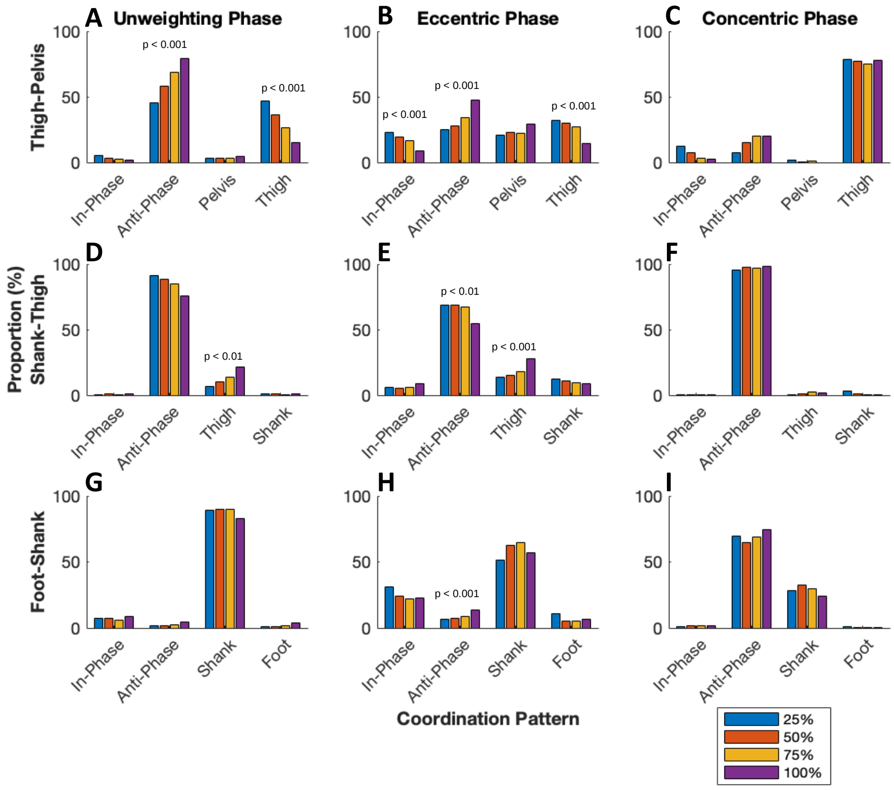

Figure 1A-1I. Mean frequency of coordination patterns (n=16) across four jump heights (25%, 50%, 75%, and 100% of maximum jump height) for all phases of the countermovement jump in the thigh-pelvis (A-C), shank-thigh (D-F), and foot-shank (G-I) segment couples. Significant main effects are presented with p values.

DISCUSSION: The coupling angles and frequency of lower extremity coordination patterns found in this analysis align well with the one previous study describing intersegmental coordination in the countermovement jump (Raffalt et al., 2016). This research is the first to describe the coordination patterns of the lower extremity in submaximal and maximal countermovement jumps and suggests that the coordination pattern behaviours in the task change based on the height of the jump (Newell, 1986). Notably, the greatest number of coordination pattern frequency changes across jump heights was in the thigh-pelvis segment couple. The idea that proximal segments are greater contributors to differences in submaximal and maximal jumps than distal segments has been suggested previously (Lees et al., 2004; Vanrenterghem et al., 2004) in joint-specific analyses. The current study expands on the work by Vanrenterghem et al. (2004) by not only demonstrating that the movement at the hip changes the most across jumps of different heights, but also describing the specific segment rotations that create these changes. For example, there is a more prominent anti-phase coordination pattern in the thigh-pelvis segment couple (thigh and pelvis are rotating away from each other) in higher jumps, and more prominent thigh-leading behaviour in lower jumps (the thigh alone is moving) in the initial descent into the countermovement. This type of description was not previously possible with uni-segmental or joint analyses, and the coordination analysis done in this study allows for a more descriptive identifcation of the kinematic output in the execution of the jump. Additionally, by breaking the countermovement jump into the unweighting, eccentric, and concentric phases, the results of this study show that all changes in the coordination pattern frequency occurred in the unweighting and eccentric phases. Our findings agree with recent countermovement jump research that identifies the eccentric phase as vital to jump performance (Barker et al., 2018), pointing to the notion that in order to jump to different heights, an athlete is altering their countermovement coordination strategy (Salles et al., 2011), but keeping the movement pattern of the push-off the same.

CONCLUSION: Using vector coding, we illustrated that the proximal segment couple coordination patterns and coordination patterns in the eccentric phase of the movement were the most responsive to changes in jump height. This finding is more informative than traditional kinetic analyses, unable to be used by practitioners in the field, or simple uni-segmental analyses, unable to understand specifically how segments are moving with respect to each other. These results expand on previous findings in coordination analyses of the countermovement jump to describe observable differences in countermovement jumps of increasing heights. Being able to characterize the intersegmental movements of the lower extremity and understanding how athletes progress through different heights can be used to guide and structure cueing techniques for athletic training or track progress of athletes recovering from lower extremity injuries. This work can be used to develop strategies or training for athletes who are not exhibiting typical progressions of lower extremity coordination from submaximal to maximal jump heights.

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